Surface Water and Ocean Topography Mission (SWOT§) Project

Science Requirements Document

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CHANGE LOG

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1- SWOT Mission Objectives

The Surface Water and Ocean Topography (SWOT) mission has been recommended by the National Research Council decadal survey "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" for implementation by NASA. The SWOT mission is a partnership between two communities, physical oceanography and hydrology, to share high vertical accuracy and high spatial resolution topography data produced by payload configuration, whose principal instrument is the Ka-band Radar Interferometer (KaRIN) for making swath measurement of the elevation of land surface water and ocean surface topography. The SWOT mission will provide a transition from the conventional profile altimeter to swath altimeter for both oceanographic and hydrologic applications in the future. The broad scientific objectives specified by the NRC decadal review have been refined by community involvement in open workshops and the guidance of an informal science team before the missions' Phase A, and further improved by the missions' Science Definition Team during Phase A. A summary of the scientific objectives for each community is given below:

1.1 Oceanography Objectives

The primary oceanographic objectives of the SWOT mission are to characterize the ocean mesoscale and submesoscale circulation determined from the ocean surface topography at spatial resolutions of 15 km (for 68% of the ocean). (Spatial resolution is defined to be wavelength in the oceanographic context.)

Current altimeter constellations can only resolve the two-dimensional ocean circulation at resolutions larger than 200 km. Fundamental questions on the dynamics of ocean variability at scales shorter than 200 km, the mesoscale and submesocale processes, such as the formation, evolution, and dissipation of eddy variability (including narrow currents, fronts, and quasi-geostrophic turbulence) and its role in air-sea interaction, are to be addressed by the new observations.

Kinetic energy and tracer transports

Global study of the circulation at scales of 15 -200 km is essential for quantifying the kinetic energy of ocean circulation and the ocean uptake of heat and carbon that are key factors in climate change. Exchange of heat and carbon between the ocean and the atmosphere is regulated by the large-scale mean circulation, as well as by the mesoscale and submesoscale eddies. Traditional altimeters have revealed the fundamental role of mesoscale eddies in the horizontal transport of heat and carbon. The uptake of heat and carbon by the ocean is complete only after the vertical transport process from the surface turbulent boundary layer into the ocean interior is accomplished. The vertical transport is mostly accomplished by the submesoscale fronts with horizontal scales 15 - 50 km. The SWOT mission will open a new window for studying these processes.

Climate change and ocean circulation

The new knowledge of the kinetic energy of the ocean circulation and the vertical transport of carbon and heat is crucial for understanding the role of the ocean in regulating climate change through the interaction of the mesoscale and submesoscale variability with the large-scale circulation. Accurate knowledge of the large-scale circulation is thus also required to achieve these objectives, posing a requirement on measurement accuracy from the submesoscale to the global scale.

Coastal ocean dynamics

Coastal ocean dynamics are important for many societal applications. They have smaller spatial and temporal scales than the dynamics of the open ocean and require finer-scale monitoring. SWOT will provide global, high-resolution observations in coastal regions for observing coastal currents and storm surges. While SWOT is not designed to monitor the fast temporal changes of the coastal processes, the swath coverage will allow us to characterize the spatial structure of their dynamics when they occur within the swath.

Coastal tides and internal tides

The new capability of mapping sea surface height down to 15 km scales will improve the knowledge of coastal tides as well as internal tides that have not been well sampled by conventional altimetry. This new information is not only crucial for achieving the ocean circulation objectives by separating tidal signals from circulation signals, but is also important for applications in both coastal and open oceans (such as navigation in the coastal ocean and improved understanding of ocean mixing in the open ocean).

1.2 Hydrology Objectives

The SWOT mission will provide measurements of water storage changes in terrestrial surface water bodies and will provide estimates of discharge in large (wider than 100 m (baseline) or 170 m (threshold)) rivers, globally. NASA has been developing missions for the global measurement of the water cycle: the Global Precipitation Mission (GPM) will measure precipitation globally, the Soil Moisture Active Passive mission (SMAP) will measure near-surface soil moisture, and the GRACE Follow-On mission will measure the changes in continental water masses. The SWOT measurements will provide a key complement to these measurements by directly measuring the surface water (lakes, reservoirs, rivers, and wetlands) component of the water cycle. The hydrologic science measurement objectives of the SWOT mission are:

1. **To provide a global inventory of all terrestrial surface water bodies whose surface area exceeds $(250m)^2$ (goal: $(100m)^2$, threshold: $1km^2$) (lakes, reservoirs, wetlands) and rivers whose width exceeds 100m (goal: 50m, threshold: 170m).**
2. **To measure the global storage change in terrestrial surface water bodies at sub-monthly, seasonal, and annual time scales.**
3. **To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.**

The primary hydrologic objectives of the SWOT mission are to characterize the spatial and temporal variations in surface waters, globally, and thus address the following hydrologic science questions:

What are the temporal and spatial scales of the hydrologic processes controlling surface water storage and transport across the world's continents?

What are the spatially distributed impacts of humans on surface water, for example through water impoundment behind dams, withdrawals and releases to rivers and lakes, trans-boundary water sharing agreements, diversions, levees, and other structures?

What are the regional- to global-scale sensitivities of surface water storages and transport to climate, antecedent floodplain conditions, land cover, extreme droughts, and the cryosphere?

Can regional and global extents of floodable land be quantified through combining remotely sensed river surface heights, widths, slopes, and inundation edge with coordinated flood modeling?

What are the hydraulic geometries and three-dimensional spatial structures of rivers globally, knowledge of which will improve our understanding of water flow?

Terrestrial Water Cycle

In its most basic form, the terrestrial water balance of any basin during a given time period is expressed as $\Delta S = P - ET - Q$, where S is total storage, P is precipitation, ET is evapotranspiration and Q is the net of all surface water discharges and groundwater flows into and out of the basin. SWOT will provide the first global inventory of the surface water components in ΔS and Q. The scientific value of these will provide a quantum improvement on our current understanding of global fresh water dynamics. For example, some Arctic basins are experiencing increases in river discharge, yet the magnitude of surface water storage change remains unknown leaving open questions regarding the underlying physical processes and their relationship to climate change.

Floodplains and Wetlands

Floodplains and wetlands in large lowland tropical basins such as the Amazon and Congo are massive in size, yet the amount of water flowing through them remains unknown. This deficiency results in poor knowledge of the amounts of water exchanged between mainstem channels, floodplains, wetlands, and uplands. An important role of these floodplains and wetlands is regulating carbon exchange with the atmosphere via CO_2 and CH_4 (carbon dioxide and methane) evasion directly from the water into the atmosphere. The water surface area and the changes in depth, both measured directly by SWOT, help govern rates of exchange.

Transboundary Rivers and Water Resources

Beyond improved characterization of the water cycle, meeting these science objectives will enable applications of scientific, social, and political importance.

Reservoirs created to store water number in the hundreds of thousands, yet a regular accounting of the water stored and annually moving through them is not available. The amount is likely substantial on a global basis, with estimates of over 5000 km^3 of water stored in the largest 1000 reservoirs. The amount is unknown for the thousands of remaining reservoirs.

Rivers crossing international boundaries pose special problems for water management. Because of a variety of reasons, upstream flows in some countries are not readily shared with downstream countries. SWOT measurements will permit all countries in a water basin to equally know the water flows and thus better manage the water volumes.

Floods resulting from either fluvial processes or storm surges cause great losses in terms of life and economy. While SWOT is not designed to target specific flood events, the swath coverage will allow the measurement of floodwater elevations for any event within the swath. Thus, SWOT data can provide useful target of opportunity information for flood events, both in near-real time and post-event analysis.

1.3 Synergistic Science Applications

In addition to the mission objectives listed above, the SWOT data will be useful for a variety of other scientific applications. Although these applications will not drive the mission requirements or cost, they are of synergistic value to the mission's science return. Therefore the mission design decisions will not preclude them, assuming that enabling these science applications will have small or no impact on the mission design or cost.

Although it is impossible to foresee all the applications that could be made of the SWOT data, a number of applications are natural candidates for consideration:

1. SWOT data can be complementary to the operational oceanographic altimeters in the TOPEX/Poseidon, Jason series, to improve the understanding of global and regional sea level change, primarily for scientific and not operational purposes.
2. SWOT data can potentially be used for mapping the thickness of floating sea ice by measuring sea ice freeboard.
3. SWOT data can potentially be used for measuring the topography of part of the Greenland and Antarctic ice sheets, and their changes.
4. The SWOT data can be used to estimate the global ocean mean sea surface and surface slopes. These data can be used to improve estimates the ocean bathymetry at higher resolution and accuracies than currently possible.
5. SWOT can collect data over the tidally affected portions of rivers, and estuaries and wetlands, to help better understand the dynamics of freshwater/marine interaction dynamics.

6. SWOT data can be used to improve the Earth's mean land/ice topography, its changes and potential land-cover classifications.
7. SWOT water surface elevation data over large lakes could allow the determination of the vertical deflection due to gravity changes by using the computation of mean lake surface undulations.
8. SWOT could provide valuable information for modeling water circulation in large lakes such as the Caspian Sea, African lakes, Lake Baikal and Lake Titicaca, and the Great Lakes of North America.

2- SWOT Science Specifications

2.1 Key Terms and Definitions

2.1.1 Requirement.

A "requirement" as used in this document specifies a condition, parameter, or capability with which the system design must be compliant, verifiable, and have a demonstrated achievement during the mission. All requirement statements are preceded by the word "Requirement" and use the verb "shall".

2.1.2 Goal.

A "goal" as used in this document specifies a condition, parameter, or capability with which the system design will strive to be compliant but it is not mandatory that such compliance be verifiable or have a demonstrated achievement during the mission. Mandatory compliance or demonstrated achievement are not required because the capabilities in the SWOT systems limit the performance, because the inherent technical difficulty with the achievement is too great, or because cost of achievement is too large. Nevertheless, a goal is tracked like a requirement so if resources or capabilities permit compliance, better system performance will result. All goal statements are preceded by the word "Goal" and use the verb "will".

2.2 Baseline/Threshold Science Missions

Science requirements for the SWOT mission are categorized into three levels: Science Goals (SG), Baseline Science Mission (BSM) Requirements and Threshold Science Mission (TSM) Requirements. The Baseline Science Mission forms the basis for the initial Project Implementation Plan and the requirements shall be achieved unless the resources of the Project are insufficient to accomplish them. The Threshold Science Mission Requirements must be achieved to avoid losing the fundamental science value of the mission and the threshold justification for the flight of the mission. Descoping to the Threshold Science Mission requirements will be exercised only when the resources of the Project are insufficient to implement the BSM and only after other descope options have been explored. Science Goals are defined here so that the SWOT engineering team can decide how to make trades and where to apply resources that might otherwise go unused.

Unless otherwise indicated, requirements are written to reflect the Baseline Science Mission. Threshold Science Mission Requirements are labeled as [TSM Requirement].

2.3 Mission Payload

2.3.1 [Requirement] The core SWOT payload shall consist of KaRIN, a Ka-band radar interferometer capable of making the swath topographic measurements with the coverage, precision and resolution given below.

2.3.2 [Requirement] The payload shall include a precision orbit determination (POD) system enabling orbit determination to support oceanography and hydrology precision and accuracy requirements listed below.

2.3.3 [Requirement] In order to meet the long-wavelength oceanography objectives and the KaRIN cal/val requirement (2.7.7) and goal (2.7.8), profile topography measurements shall be available with an accuracy equal or better than the Jason series of altimeters and radiometers, as well as their POD performance, and with a sampling compatible with the SWOT calibration needs.

The baseline mission requires that these measurements be collected by a Jason-class altimeter/radiometer combination located on the same platform as KaRIN. In addition, it may be possible to use profiling ocean topography measurements from other missions flying at the same time. A baseline payload suite meeting these requirements is assumed to be:

1. *A dual-frequency (Ku and C-band) altimeter with capabilities similar to the Poseidon altimeter on OSTM/Jason-2.*
2. *A 3-frequency radiometer similar to the Advanced Microwave Radiometer (AMR) on OSTM/Jason-2, but with the capability of imaging across the swath.*

However, other collocated solutions may exist that provide the required calibration performance.

2.3.4 [Requirement] Capabilities to measure water vapor across the swath over the ocean shall be implemented.

2.4 Mission Lifetime

2.4.1 [Requirement] The Baseline Science Mission shall operate for at least 42 months, including three annual cycles (36 months), a 3-month phase of launch/early operation and payload check out, and a 3-month fast-sampling calibration phase (including orbit transition).

A minimum of three years is required to sample seasonal and inter-annual variability for both the ocean and surface water height changes appropriately. The 36 months include an 8-month measurement validation phase. It is expected that these phases will produce valid science data after suitable reprocessing with the calibrated instrument parameters.

2.4.2 [TSM Requirement] The Threshold Science Mission shall operate for at least 18 months, including one annual cycle (12 months), a 3-month phase of launch/early operation and payload check out, and a 3-month fast-sampling calibration phase (including orbit transition).

The Threshold Science Mission is required to sample the seasonal variability for one year.

2.5- Space-Time Sampling Requirements

2.5.1 [Requirement] The SWOT sampling for the Baseline Science Mission shall minimize aliasing of ocean tidal signals.

Tidal signals must be removed from the ocean topography data in order to meet the mesoscale and submesoscale measurement requirements and associated annual and interannual variability. This requirement precludes the use of a sun-synchronous orbit, which aliases solar tides into a very long period signal.

2.5.2 [Requirement] The SWOT orbit inclination for the Baseline Science Mission shall lie between 74º and 78º.

A minimum of 74 deg inclination is required to cover all important hydrology land targets. Extending the inclination to 78 deg is required to cover important polar ocean areas and still meet the tidal aliasing requirement. This will also cover a large part of the Greenland and Antarctic ice sheets, particularly in the highly variable coastal regions.

2.5.3.a [Requirement] The SWOT orbit shall be a repeat orbit with a maximum repeat period of 23 days and a minimum repeat period of 21 days.

With swath coverage, ascending and descending pass swath coverage implies an average revisit time on the order of approximately 11 days at low latitudes. This temporal sampling is similar to that obtained by OSTM/Jason-2 and better than the GEOSAT and GFO ocean altimeter missions. For surface water, an 11-day revisit period allows appropriate sampling of river dynamics in the tropics. At high latitudes, the swath sampling will produce shorter revisit periods, compatible with arctic river dynamics. This temporal sampling choice is a required trade-off for maintaining global coverage including the high-latitude regions and for minimizing the tidal aliasing.

2.5.3.b [Requirement] The SWOT orbit ground track shall be controlled to within +/- 1 km at least 90% of each year, and not exceed +/- 2.5 km.

The orbit control requirement is somewhat relaxed compared to the Jason altimeter series, due to improved knowledge of the mean sea surface, and is required for minimization of geoid error contribution to the ***nadir*** *altimeter.*

2.5.4.a [Requirement] SWOT shall collect data over a minimum of 90% of all ocean and land areas covered by the orbit inclination for 90% of the operation time. This requirement does not apply to the fast sampling calibration/validation phase described in 2.5.5. This requirement also does not apply when 1) the KaRIN measurement is not physically feasible, including ice or snow covered surface water; surface water in regions of extreme topographic layover, or situations where the rain rate is greater than 3 mm/hour and 2) when the KaRIN measurement is not expected to meet performance requirements during maneuvers, thermal snaps (the solar arrays and/or the KaRIN mast), and rotations of the solar arrays for sun tracking.

This requirement is similar to that levied for TOPEX/Poseidon and Jason time series. The requirement ensures that geographic gaps in coverage shall be smaller than 10% of the Earth's surface available to the mission. The requirement can only be met by a swath instrument if one takes into account the temporal sampling requirement.

The coverage requirement cannot be levied when the physical circumstances make the measurement unfeasible or unreliable. It is impossible to measure water level when the water is covered by ice or snow, as will be the case for boreal regions in Northern Hemisphere winter. The coverage of rivers, lakes, and wetlands in areas of extreme topography is also limited by topographic layover. Although in some situations topographic layover will produce errors within the surface water requirements, certain rivers and lakes in regions of extreme topography will be systematically contaminated by topographic layover, independent of choices in the instrument design. Finally, rain rates above 3mm/hour severely attenuate the radar signal, making the measurement unfeasible. At any given time, about 7% of the Earth's surface will experience these rain rates.

2.5.4.b [Requirement] The total duration that the KaRIn measurements will not meet performance requirements due to maneuvers, thermal snaps (the solar arrays and/or the KaRIN mast), and rotations of the solar arrays for sun tracking shall not exceed 5% of the mission operation time.

2.5.4.c [TSM Requirement] ***SWOT shall collect data over a minimum of [22]% of all areas covered by the orbit inclination. This requirement does not apply to the fast sampling calibration/validation phase described in 2.5.5. This requirement also does not apply when the KaRIN measurement is not physically feasible, including (1) ice or snow covered surface water; surface water in regions of extreme topographic layover, or situations where the rain rate is greater than 3 mm/hour, or (2) when the KaRIN measurement is not expected to meet performance requirements during maneuvers, thermal snaps (the solar arrays and/or the KaRIN mast), and rotations of the solar***

arrays for sun tracking.

This threshold requirement is intended to cover anomalous situations (e.g., flight and/or ground system anomalies, etc.) that impact the ability to meet the baseline coverage and operability requirements. The minimum 22 % coverage corresponds to the case of the failure of the onboard processor, causing all data to be acquired in the high-rate mode. The capacity of the onboard recorder and the ground receiving stations does not allow 100 % download of the high-rate data. In this eventuality, a contingent sampling plan would be developed by the mission's science team to trade off available spatial and temporal coverage to achieve a reduced scope of the mission's science objectives.

2.5.5 [Requirement] SWOT shall have a fast-sampling phase after the instrument check out phase for at most 3 months

By frequent revisits of calibration sites, the fast-sampling phase will enable the calibration of radar system parameters in the shortest time, resulting in the fastest transition to the nominal phase with a fully calibrated system.

In addition, SWOT will demonstrate the first interferometry measurement of ocean water elevations at 15 km resolution, which has an unknown temporal decorrelation time. We will need to understand and validate the new measurement at the beginning of the mission to get ready for subsequent science studies. During this fast-sampling phase, we will need sufficient amount of data collected in exact repeating coverage for evaluation and comparison to other independent observations from both in-situ and spaceborne platforms. A 1-day repeat mission optimizes temporal sampling at the cost of spatial coverage. A 1-day sampling mission also optimizes the number of cal/val revisits in the fast sampling phase.

One-day repeat sampling is valuable for sampling some submesoscale and mesoscale phenomena appropriately. The 1-day sampling will give us better temporal coverage of the evolving submesoscale filament structures and fronts in the ocean. It will also be necessary for investigating certain dynamical structures in the tropics, including tropical instability waves, and the filament structures surrounding them. Coastal currents and propagating waves, and offshore squirts and jets, will also benefit from the higher frequency sampling. Measuring these phenomena is part of the SWOT ocean science objectives.

2.5.6 [Requirement] The location of the fast sampling phase orbital nodal crossing and crossovers shall be designed to meet both oceanographic and hydrology science goals.

2.6 Science Data Products and Data Product Delivery

2.6.1 [Requirement] Level-1B data products shall be produced from the payload data.

2.6.2.a [Requirement] The following Level-2 standard data products shall be produced for the ocean data in a swath-oriented, geographically-fixed grid covering the entire measurement swath and the nadir gap:

1. **Ocean sea surface heights (SSH) (including the nadir measurements according to 2.3.3).**
2. **Estimated sea surface height uncertainties (1σ) on the same grid as the SSH measurements.**
3. **Radar σ_0 measurements on the same grid as the SSH measurements.**
4. **Wind speed (but not direction) estimates derived from the radar σ_0 on the same grid as the SSH measurements.**
5. **Standard deviation of SSH performed prior to averaging from the high resolution onboard processor data to the Level 2 resolution, on the same grid as the SSH measurements.**
6. **Estimated Sea Surface Slope vector performed during the re-gridding and geolocation of the onboard processor data to the Level 2 resolution, on the same grid as the SSH measurements.**
7. **Nadir altimeter data products consistent with the Jason-series Geophysical Data Records (GDR's).**

2.6.2.b [Goal] Estimates of ocean significant wave height on the same grid as the SSH measurements.

2.6.2.c [Goal] Lower accuracy data with the same sampling characteristics as the level 2 ocean data for swath and nadir altimetry, but with degraded accuracy, will be produced in near real time (1 day-lag from data downlink) in support of operational applications.

2.6.3.a [Requirement] The following Level-2 standard data products shall be produced for the surface water data:

- **For each pass, a geolocated water mask of all water bodies identified in the data downlinked by SWOT, regardless of surface area. The mask resolution will be reported at the finest resolution consistent with meeting appropriate geolocation accuracy. The mask will be reported as a geolocated point cloud (including data described below), which will have irregular spatial sampling and varying average point separation from near to far range.**
- **As noted below, SWOT required performance will be *evaluated* using water bodies meeting the minimum size criteria set in the science requirements, i.e., water bodies with area greater than (250 m)^2 and rivers of width greater than 100 m However, the SWOT performance will be *characterized* for water bodies meeting the minimum size criteria in the science goals; i.e., water bodies with area greater than (100 m)^2 and rivers of width greater than 50 m. Only water bodies in regions of moderate topographic relief (i.e., where**

layover contamination is negligible) are to be used to assess SWOT performance.

- **Estimated surface water elevations with the same sampling as the water mask.**
- **Estimated surface water elevation uncertainties (1σ) with the same sampling as the water mask.**
- **Additional data and meta-data (e.g., collection time, water brightness) that might be required for deriving additional data products.**

The Level-2 data product is reported at the finest resolution consistent with accurate geolocation, which implies that some range and azimuth averaging ("multi-looking") will be done at the interferogram level to achieve geolocation errors that will scale as the square root of the number of samples upon further spatial averaging for derived data products. A typical conventional value for acceptable geolocation error in any direction is 10% of the pixel dimension in that direction (e.g., in the range direction, a maximum geolocation error of ~7 m is acceptable in the near range, while in the far range a ~1 m geolocation error is expected). All other hydrology data products listed below will be derived from this Level-2 data product. The elevation, mask, and error products for water bodies and rivers smaller than those over which the performance can be guaranteed will provide useful information that can be supplemented with in situ or other data to improve the science return from SWOT. Thus, these data products should be produced for all water bodies where surface water is detected by SWOT.

2.6.3.b [Requirement] A global water mask consisting of polygons denoting shorelines of rivers, lakes, wetlands, reservoirs and all surface water bodies at a spatial resolution as noted in requirement 2.8.1 shall be produced at least once every repeat cycle. For those water bodies that have an enclosed shoreline (i.e., not rivers), all water levels within the enclosed shoreline and from each repeat-cycle time-period will be averaged to provide one elevation for each individual water body. Water elevations for rivers will be produced at the spatial resolution noted in requirement 2.8.1, thus resulting in less spatial averaging compared to enclosed water bodies but still allowing for slope calculations. The water body polygons will be stored in vector format with the elevations and other relevant data stored in the attribute data for each polygon.

This data product will allow the hydrology community at large access to storage change throughout the mission. The data set will complement related existing data sets, such as the World Wildlife Fund Global Lakes and Wetlands database. The update period (e.g., one per nominal 21-day repeat cycle or pass based) will be determined by the science team. Researchers who need SWOT data at the highest spatial and temporal resolution can use the pass-by-pass data noted in requirement 2.6.3a.

2.6.3.c [Requirement] A global estimate of discharge at the time of observation (i.e., pass-by-pass), and associated discharge errors, shall be produced for all rivers that are wider than 50m. These discharge estimates will be one-dimensional vector products. The reported discharge will be an estimate of the reach-averaged

discharge, and the extent of reach averaging will be selected to reduce errors in a global water balance.

It is assumed that discharge estimates will be based on the use of a Manning equation relating the reach averaged discharge to the SWOT reach-averaged observables, which can be derived from the products in requirement 2.6.3.a. In general, when applied to the discharge product, hydrologic quantities will always refer to the reach-averaged quantities (i.e., reach-averaged stage, width, slope, cross section). Thus, the river widths in this document (i.e., 170m TSM requirement, 100 m requirement, 50 m goal) should be understood as reach-averaged river widths. Two parameters in Manning's equation, the reach averaged bathymetry and roughness coefficient, are not directly observable by SWOT, but can be derived from the observations obtained during a seasonal cycle. Further improvements in these estimates can be obtained using in situ information, when available.

2.6.3.d [Requirement] The discharge product shall be available to the science community starting six months after the SWOT validation meeting.

The global estimation and validation of these additional parameters implies that operational production of discharge can only start after one seasonal cycle and subsequent validation, hence the production timeline. This product will be updated at least one time during the mission to reflect improvements in knowledge of bathymetry and roughness together with in situ calibration.

2.6.3.e [Requirement] A final discharge data product shall be available at the end of the mission incorporating the best bathymetry and roughness information estimated during the mission.

2.6.3.f [Goal] A Level-2 standard data product will be a topographic map of all land elevations. This global digital elevation model (DEM) will be constructed from many SWOT orbits. Given the present SWOT configuration, it is not clear if sufficient signal-to-noise will be available to ensure any land elevations. Thus the height and geolocation accuracies of the DEM cannot yet be specified. Ideally, the height accuracies will be better than 1m and geolocation accuracies will be the same as those noted for the water bodies in requirement 2.6.3.b. Prior to launch, should studies demonstrate that a land DEM is not possible from SWOT, then the Project will engage with other DEM oriented satellite missions (e.g., the TanDEM-X mission) to determine the possibilities of using their global topographic data products within the overall SWOT science.

2.6.3.g [Requirement] The Level-1 single-look radar data products shall be available to selected investigators on a regional basis.

It is expected that, subsequent to launch, algorithm improvements at the finest possible resolution may be possible. Making the single-look data available on a regional basis to *selected investigators will enable refinement of SWOT algorithms, while limiting the need to distribute at large the prohibitively large global data set.*

2.6.4 [Requirement] The Level-2 point cloud products shall be produced for each pass of data collection with the following provisions. The cross-section map will be updated yearly excepting areas where floodplain and/or channel topography is dynamic on shorter time scales.

The estimation of storage change for both rivers and lakes requires known bathymetry (i.e., topography) for the case when flooding is initiated across previously dry land (e.g., the first pulse of floodwaters across a floodplain or that of a rising lake level across a low slope shore). In addition, floodplain Digital Elevation Models (DEMs) are a key data set for understanding flood dynamics and channel cross-sections are needed for estimation of stream discharge. The cross-section maps are produced by using the varying river or lake stage and extent to contour the channel topography. The channel topography maps cannot be produced for each pass since it requires the observation of the river stage history over the mission lifetime. The results of this product will be used to derive the final and intermediate discharge data products.

2.6.5 [Requirement] After the calibration phase, the Level-2 data production rate shall keep up with the data acquisition rate during the rest of the mission to avoid data backlogs and to ensure the availability of the data products to the science team within 60 days of data collection.

2.6.6 [Goal] Routine access in near real time (<30 days) to vector elevation data for a limited (<1000) number of large water bodies (e.g., reservoirs selected by the SDT) will be allowed.

Over 90% of water stored in reservoirs is contained in the largest 1000 reservoirs and access to these data will greatly benefit SWOT goals such as trans-boundary water management and monitoring. The large size of these reservoirs guarantees that one month is sufficient temporal sampling for their monitoring, and a one-month delay guarantees timely data access for monitoring. The data product will be identical to the one described in 2.6.3b restricted to the largest reservoirs and with a faster access time.

2.6.7 [Requirement] After the initial calibration phase, all Level-2 data products shall be made available for distribution to the general scientific community within 6 weeks after they are made available to the SWOT Science Team.

It is expected that data collected during the calibration phase can be used for the production of valid data products.

2.6.8 [Requirement] For distribution to the general scientific community, Level 2 products shall be accompanied by an assessment of the quality of the product relative to the measurement requirements. The quality assessment is provided by the Science Team.

2.6.9 [Goal] Reprocessing will be conducted on the SWOT Standard data products to correct for known errors and/or improved algorithms, in parallel with normal processing of incoming data.

2.6.10 [Requirement] All Level 0, 1 and 2 Standard data products shall be delivered to NASA and CNES to be placed in a permanent archive at the end of the mission.

2.7- Ocean Science Performance Specifications

In order to achieve the ocean science objectives, the following measurement science requirements and goals for the SWOT mission are imposed:

2.7.1.a [Requirement] The spatial posting of sea surface height measurements shall be no coarser than 2 km.

2.7.1.b [Goal] The spatial posting of height measurements will be no coarser than 250 m.

A measurement posting is defined as the location of the geographical center of a set of higher spatial resolution instrument height measurements which are merged to form an estimate of the sea surface height.

In order to achieve a resolution of 15 km, as set in the science objectives, a sampling of 7.5 km is required by the Nyquist sampling criterion. In order to calculate geostrophic velocities and relative vorticity, derivatives of the height field must be computed. To reduce errors in estimating these derivatives, it is required to oversample the height field relative to instrument resolution. A 2km over-sampling will achieve this requirement.

For coastal, estuarine, and ice applications, it is desirable to have the higher spatial sampling of 250 m.

2.7.2.a [Requirement] The sea surface height error spectrum (cross-track average of the along-track spectra computed at different cross-track locations over the swath) in the wavelength range smaller than 1,000 km shall not exceed the spectrum envelope given in Figure 1 and the formulas below. This requirement holds for significant waveheights (SWH) less than 2 meters.

Mapping of mesoscale and submesoscale phenomena at 15-25 km resolution requires that the measurement noise be smaller than or equal to the signal for the resolved wavelengths. It is desirable to have the signal strength be at least one order of magnitude greater than the measurement noise..

Achieving basin scale (~1,000 km to 10,000 km) SSH consistency is not required in order to meet the threshold science objectives, but will enable basin scale oceanography, as a complement to the TOPEX/Jason altimeter series.

Define the SSH error spectrum, E(f), as a function of the spatial frequency f (i.e., f=1/wavelength=1/λ) (the same as the term of "wavenumber" used in some oceanographic literature) such that the expected SSH error variance in the wavelength interval $[\lambda_{min}, \lambda_{max}]$ *is given by the integral of E(f):*

$$\left\langle (\delta h)^2 \right\rangle = \int_{1/\lambda_{max}}^{1/\lambda_{min}} E(f)\, df \qquad (1)$$

Then the SSH spectrum in the ranges defined above is given by

$$E(f) = 2 + 0.00125 f^{2}\ [cm^2/cycle/km] \quad 15\ km < \lambda < 1{,}000\ km \qquad (2)$$

which consists of a constant white noise contribution, which dominates at small wavelengths, and a correlated noise contribution, which dominates at longer wavelengths, representing residual geophysical errors, orbit and attitude restitution errors.

In the SSH validation process, the "truth" profiles used for validation of the SSH measurements is defined as profiles of the true ocean surface filtered to remove all wavelength components with wavelengths smaller than 15 km.

Because KaRIN will make 2 dimensional measurement, the noise can be reduced by 2-d smoothing to a level lower than by 1-d smoothing. To resolve 15 km wavelength, the Nyquist is 7.5 km. Therefore the noise is to be smoothed over a domain of 7.5 km x 7.5 km. Along-track wavenumber spectrum is then performed on the 2-d smoothed SSH at various locations across the swath. The average of such spectra is then evaluated against the requirement. The requirement should only be imposed to wavelengths of 15 km and longer. However, the data should be posted at 1km or 250m pixels without the 2-d smoothing, which is only to be applied for evaluating the spectral performance.

Due to the inherent noise in estimating the spectrum of a noisy process, validation of this requirement is understood in an ensemble sense, to insure that the estimation errors associated with the error spectral power for any given frequency are suitable to insure that the requirement has been met with a probability greater than 68%.

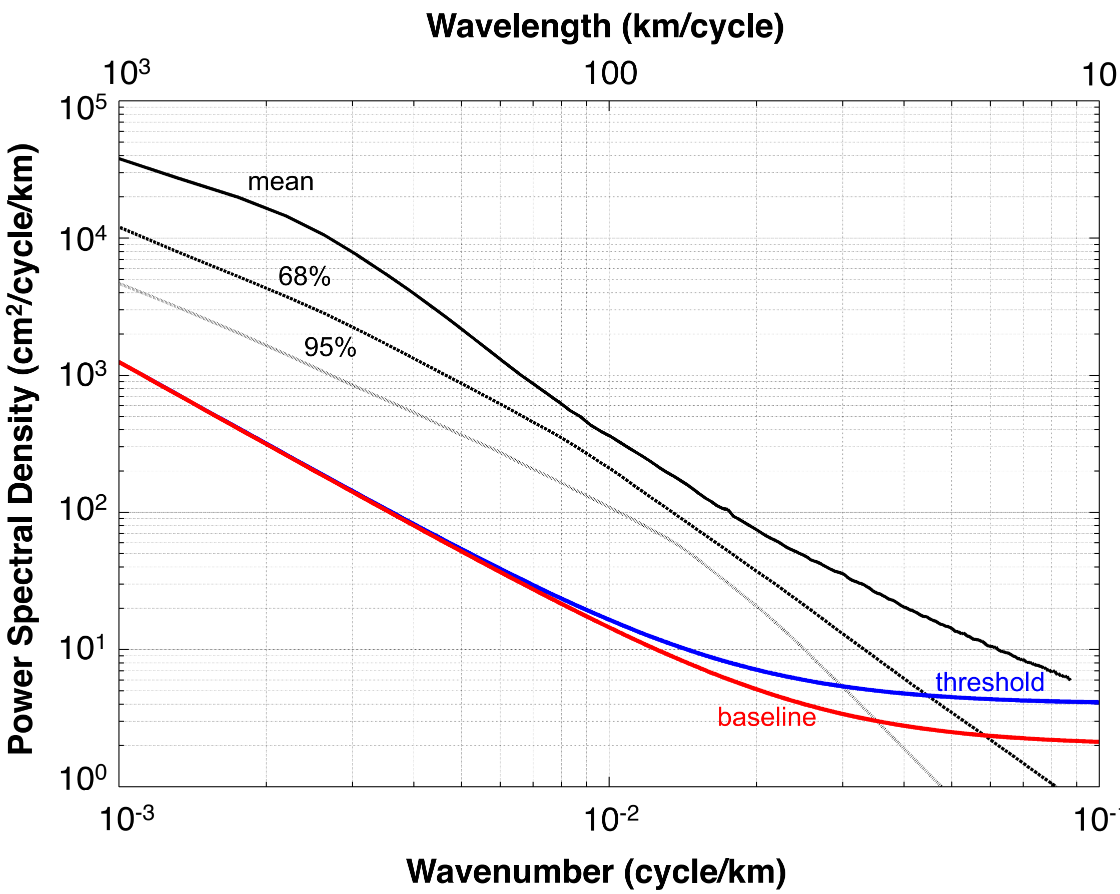

Figure 1: *SSH baseline requirement spectrum (red curve) as a function of wavenumber. Blue curve is the threshold requirement. Shown, for reference is the global mean SSH spectrum estimated from the Jason-1 and Jason-2 observations (thick black line), the lower boundary of 68% of the spectral values (the upper gray dotted line), and the lower boundary of 95% of the spectral values (the lower gray dotted line). The intersections of the two dotted lines with the baseline spectrum at ~ 15 km (68%) and ~ 25 km (95%) determine the resolving capabilities of the SWOT measurement. The respective resolution for the threshold requirement is ~ 20 km (68%) and ~ 30 km (95%).*

The SWH requirement is consistent with the Jason requirement of operations for SWH < 2m.

2.7.2.b [Goal] The white noise component of the error spectrum will not exceed 1 cm^2/cycle/km.

This noise level, consistent with a spatial resolution of 12 km for the SSH spectrum shown above (compared to the 15 km spatial resolution requirement for the Baseline Science Mission) will yield improved understanding of ocean submesoscale circulation, internal *tides, and non-geostrophic contributions to SSH at scales consistent with small submesoscale phenomena.*

2.7.2.c [TSM Requirement] The Threshold Science Mission white noise component of the error spectrum shall not exceed 4 cm^2/cycle/km.

This noise level, consistent with a spatial resolution of 20 km for the SSH spectrum shown above (compared to the 15 km spatial resolution for the Baseline Science Mission) will still yield significant science results for high-frequency ocean mesoscale and surface water studies. The key contribution of the SWOT mission to oceanography is in the study of mesoscale and submesoscale phenomena. Measuring longer scales is not critical to the threshold mission success, although it would demonstrate the consistency with the previous altimeter data record and provide a complement to the altimeter constellation flying at the same time as SWOT.

2.7.3 [Requirement] The height postings shall be geographically fixed, and independent of spacecraft position and attitude.
The measurement geographic grid needs to remain constant over the mission to minimize geoid errors and enable the construction of a mean sea surface and variability studies.

2.7.4 [Requirement] SWOT shall provide flagging of height postings affected by rain with 68 % accuracy of the rain (More than 68% of rain-contaminated data must be correctly flagged).

Rain cells significantly distort Ka-band radar measurements due to signal attenuation. An estimated 5%-10% of all data (depending on latitude) will be affected by rain events. This specification is inherited from the OSTM mission requirements for rain flagging.

2.7.5 [Requirement] SWOT shall provide flagging of sea ice over the ocean with 68 % accuracy of the sea ice flag. (More than 68% of sea-ice-contaminated data must be correctly flagged.)

2.7.6 [Requirement] The SWOT ocean performance shall be verified by payload independent measurements or analysis during a post-launch calibration/validation period.

2.7.7 [Requirement] The cross-track averaged SSH from KaRIN shall be cross-calibrated against the nadir altimeter at wavelengths shorter than 1000 km and longer than 200 km with an aim for consistency to the extent of the accuracy of the nadir altimeter.

The nadir altimeter measurement is affected by instrument noise at wavelengths shorter than 200 km. At 200-1000 km, the performance of KaRIN is to be evaluated by comparison to the nadir altimeter measurement.

2.7.8 [Goal] The cross-track averaged SSH from KaRIN will be cross-calibrated against the nadir altimeter at wavelengths longer than 1000 km with an aim for consistency to the extent of the accuracy of the nadir altimeter.

Although there is no requirement levied on the performance of KaRIN at wavelengths longer than 1000 km, its performance is to be assessed by comparison to the nadir altimeter measurement. It is a goal of the mission for assessing the performance of KaRIN for observing ocean variability at all scales.

2.8- Surface Water Science Performance Specifications

In order to achieve the surface water science objectives, the following measurement science requirements and goals for the SWOT mission are imposed:

2.8.1 [Requirement] The post separation for surface water Level-2 data shall be consistent with (1) the finest spatial separation commensurate with geolocation accuracy; (2) minimization of the estimation errors for irregular water bodies; (3) cross-swath variation with maximum less than the 70m range resolution in the near swath.

2.8.2.a [Requirement] The surface water areas estimated using the Level-2 water mask (requirement 2.6.3a) shall have a relative error smaller than 15% (1σ) of the total water body area for water bodies whose surface area exceeds $(250m)^2$ or river reaches whose width exceeds 100 m on average and length exceeds 10 km.

2.8.2.b [TSM Requirement] The surface water areas estimated using the Level-2 water mask (requirement 2.6.3a) shall have a relative error smaller than 15% (1σ) of the total water body area for water bodies whose surface area exceeds $1km^2$ or river reaches whose width exceeds 170 m [TBC] on average and length exceeds 10 km.

2.8.2.c [Goal] The surface water areas estimated using the Level-2 water mask (requirement 2.6.3a) will have a relative error smaller than 25% (1σ) of the total water body area for water bodies whose surface area is between $(100m)^2$ and $(250m)^2$ or river reaches whose width is between 50 m and 100m on average and length exceeds 10 km.

2.8.3 [Requirement] The lake, reservoir, and wetland height accuracy of the Level-2 data (requirement 2.6.3.a) shall be (1) 10 cm (1σ) or better, for water bodies whose surface area exceeds 1 km^2 and (2) 25 cm or better for water bodies whose surface area is between $(250m)^2$ and 1 km^2.

To measure storage change, only relative changes in water level are required. The $(250m)^2$ size requirement is consistent with the river precision requirement, 2.8.4, and is *expected to capture up to 65% of lake storage changes, which will be a significant advance compared with the current capability, which is estimated to capture only 15% of the storage variability. The 1km^2 lake area threshold requirement will capture an estimated 50% of storage variability and still represents a significant improvement over current knowledge. The baseline 100 m river width requirement is for resolving river basins larger than 50,000 km^2 at 70% globally, which will be a significant advance beyond the current capability. The 170 m threshold river width requirement is for resolving river basins larger than 150,000 km^2 at 70 % globally. Observations at this level of performance would still improve on the historical gauge network, especially in areas like the Congo basin that are currently poorly observed.*

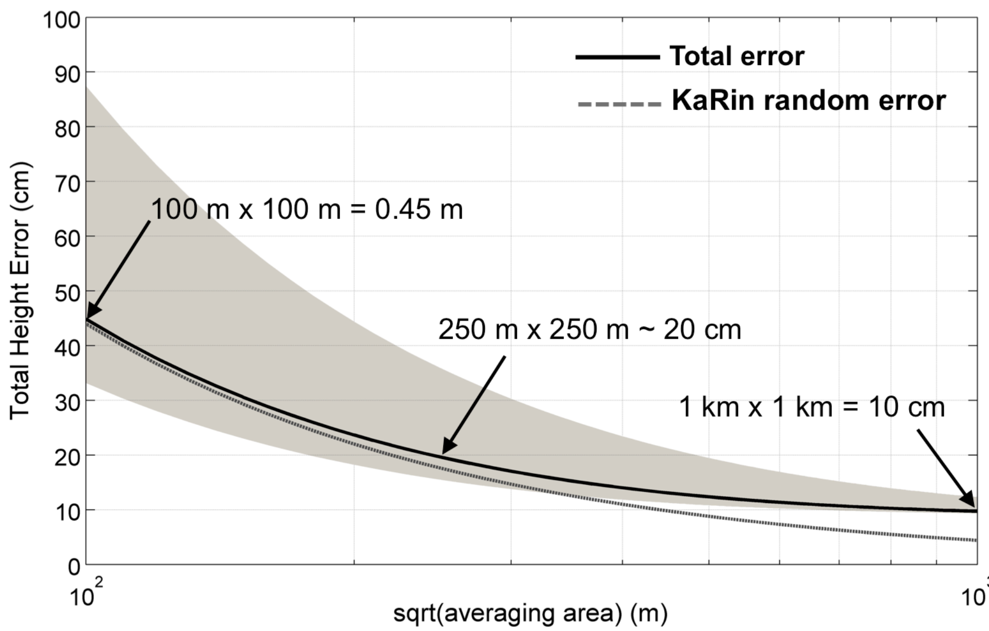

Figure 2: *Estimated water body total height accuracy for water-only pixels as a function of averaging area used to form the estimate (solid curve). Shown, for reference, is the KaRIN random error only contribution to the height accuracy (dashed curve). The total height accuracy is 10 cm for an equivalent water area of 1 km^2, 21 cm for (250 m)^2, and 50 cm for (100 m)^2. Due to changes in spatial resolution and signal-to-noise-ratio, the performance will vary across the swath. The shaded area shows the expected variability in performance as a function of the averaging area.*

2.8.4 [Requirement] Using the pass-by-pass data of requirement 2.6.3.a, after processing elevations, river height accuracy shall be (1) 10 cm (1σ) or better over an area of 1 km^2 inside the river mask, and (2) 25 cm or better for water bodies whose surface area is between (250m)^2 and 1 km^2.

All river requirements assume that the elevations are processed to average height and slope by fitting a polynomial of suitable order to the irregularly sampled elevation data. The requirement applies for any given location along the river reach where the minimum width requirements are met.

2.8.5 [Requirement] Using the Level-2 data of requirement 2.6.3a, after processing elevations over a maximum 10 km of flow distance, river water slope accuracy shall be 1cm/1km (10 μrad) (1σ) or better for river widths greater than 100 m.

The accuracy of the estimated slope depends on both the length of the averaging reach and the width of the river. For rivers whose reach-averaged width is greater than 100 m, the length of the flow distance required to meet the 10 μrad requirement will be smaller, while it will be greater for rivers whose reach-averaged width is smaller than 100 m. The dependence on the averaging reach and the river width is presented in the following figure.

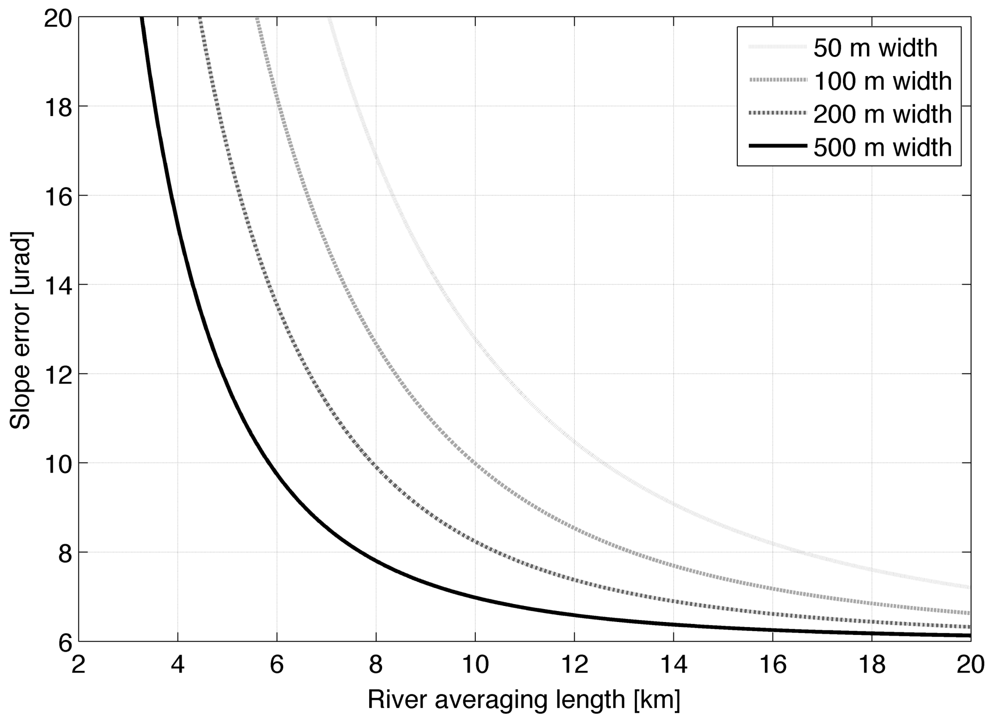

Figure 3*: River slope error (in μrad) as a function of river averaging length (in km) for reach-averaged river widths from 50 m to 500 m based on a height performance consistent with Figure 2.*

2.8.6 [TSM Requirement] Using the pass-by-pass data of requirement 2.6.3a, the lake, reservoir, and wetland height accuracy shall be 11 cm (1σ) or better, for water

bodies whose surface area exceeds 1 km^2. For TSM, no requirement is levied against smaller water bodies.

2.8.7 [TSM Requirement] Using the pass-by-pass data of requirement 2.6.3a, after processing elevations over an area of 1 km^2 inside the river mask, river height accuracy shall be 11 cm (1σ) or better. For TSM, no requirement is levied against smaller rivers.

2.8.8 [TSM Requirement] Using the Level-2 data of requirement 2.6.3a, after processing elevations over a maximum 10 km of flow distance, river water slope accuracy shall be 2cm/1km (20 μrad) (1σ) or better for river widths greater than 100 m.

These threshold science requirements will still enable significant advances on our current knowledge of global water balance.

2.8.9 [Requirement] SWOT shall provide flagging of height postings affected by rain in both the pass-by-pass and global data, with 68% accuracy of the rain flag.

Rain cells significantly distort Ka-band radar measurements due to signal attenuation. An estimated 5%-10% of all data (depending on latitude) will be affected by rain events.

2.8.10 [Requirement] SWOT shall provide flagging of height postings affected by topographic layover in both the pass-by-pass and global data, with 68% accuracy of the layover flag.

Topographic layover (radar energy from surrounding topography or vegetation and arriving at the same time as the water signal) can significantly affect the height error, if the layover radar energy is sufficiently great compared to the water return.

2.8.11 [Requirement] SWOT shall provide flagging of frozen surface water in both the pass-by-pass and global data, with 68% accuracy of the frozen water flag.

2.8.12 [Requirement] The SWOT surface water elevation shall be verified by a payload independent measurement or analysis during a post-launch validation period as well as during the mission lifetime.

2.8.13 [Requirement] The SWOT surface water discharge equations shall be calibrated for unknown bathymetry and roughness coefficient by observation of river dynamics and the use of in situ and *a priori* data collected on selected water bodies pre and post-launch.

2.8.14 [Requirement] The SWOT discharge performance shall be quantified by a payload independent measurement or analysis during a post-launch validation period as well as during the mission lifetime.

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